

# The Low-Mass Stellar IMF at High Redshift: Faint Stars in the Ursa Minor Dwarf Spheroidal Galaxy<sup>1</sup>

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## 1. Introduction

Low-mass stars, those with main-sequence lifetimes that are of order the age of the Universe, provide unique constraints on the Initial Mass Function (IMF) when they formed. Star counts in systems with simple star-formation histories are particularly straightforward to interpret, and those in ‘old’ systems allow one to determine the low-mass stellar IMF at large look-back times and thus at high redshift. We present the faint stellar luminosity function in an external galaxy, the Ursa Minor dwarf Spheroidal (dSph). This relatively-nearby (distance  $\sim 70$  kpc) companion galaxy to the Milky Way has a stellar population with narrow distributions of age and of metallicity (e.g. Hernandez, Gilmore & Valls-Gabaud 1999), remarkably similar to that of a classical halo globular cluster such as M92 or M15, i.e. old and metal-poor ( $[\text{Fe}/\text{H}] \sim -2.2$  dex). The integrated luminosity of the Ursa Minor dSph ( $L_V \sim 3 \times 10^5 L_\odot$ ) is also similar to that of a globular cluster. However, the central surface brightness of the Ursa Minor dSph is only 25.5 V-mag/sq arcsec, corresponding to a central luminosity density of only  $0.006 L_\odot \text{pc}^{-3}$ , many orders of magnitude lower than that of a typical globular cluster. Further, again in contrast to globular clusters, its internal dynamics are dominated by dark matter, with  $(M/L)_V \sim 80$ , based on the relatively high value of its internal stellar velocity dispersion (Hargreaves *et al.* 1994; see review of Mateo 1998). Faint star counts in the Ursa Minor dSph thus allow determination of the low-mass IMF in a dark-matter-dominated external galaxy, in which the stars formed at high redshift.

## 2. Observations

We obtained deep imaging data with the Hubble Space Telescope, using WFPC2 (V-606 & I-814), STIS (LP optical filter) and NICMOS (H-band), in a field close to the center of the Ursa Minor dSph (program GO 7419: PI Wyse, Co-Is Gilmore, Tanvir, Gallagher & Smecker-Hane; due to successive failures of HST the data acquisition phase of this project remains ongoing). The estima-

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tion of the contamination by foreground stars and background galaxies required acquisition of similarly-exposed data for an offset field  $\sim 2$  tidal radii away from the Ursa Minor dSph, at similar Galactic coordinates to the UMi field ( $\ell = 105^\circ$ ,  $b = 45^\circ$ ); this field shows no evidence for Ursa Minor member stars.

### 2.1. WFPC2 Data for the Ursa Minor dSph

The WFPC2 data are discussed in more detail in Feltzing *et al.* (1999). They consist of  $8 \times 1200$ s in each of F606W and F814W filters. Standard HST data reduction techniques were followed using the IRAF STSDAS routines, with photometry on the reduced images using DAOPHOT and TinyTim psf's. The scatter in the zero points and photometric calibrations is  $\sim 6\%$ , which is small compared to the 0.5 magnitude binning we adopt for the luminosity functions below. Identical procedures were applied to both the UMi and the offset-field datasets. The completeness of the data was determined by adding artificial stars to the original images and then re-processing them. The luminosity functions discussed below include only stars detected in both V and I.

### 2.2. STIS LP data for the Ursa Minor dSph & M15

We obtained seven 2900s exposures of each of the Ursa Minor field and the offset field. We also obtained a single exposure (1200s) of the globular cluster M15 in a field with extant deep WFPC2 V and I data (Piotto, Cool & King 1997). The metallicity and age of the stars in M15 are very similar to those in the Ursa Minor dSph and the STIS LP magnitudes for the Ursa Minor dSph may be transformed to I-814 using the extant M15 I-814 data (courtesy of G. Piotto). Standard data reduction procedures as above were applied to our data.

## 3. Faint Luminosity Functions

### 3.1. Globular Clusters

We utilise comparisons between the data for the Ursa Minor dSph and globular clusters of the same metallicity and age (M92 and M15). A direct comparison between the luminosity functions corresponds to a comparison between the underlying stellar mass functions. However, the stellar mass function in globular clusters may be modified by both internal and external effects and thus in not all cases is the present-day mass function a good estimate of the initial mass function. The Piotto, Cool & King (1997) data were obtained at intermediate radius within M15 and M92, where the effects of mass segregation are expected to be small and the local faint luminosity function should be a good estimate of the global faint luminosity function. Further, as discussed by Piotto & Zoccali (1999), M92 and M15 have fairly steep main-sequence luminosity functions, while other globular clusters, particularly those for which external dynamical effects such as tidal shocking by the disk or bulge of the Milky Way may be important, have flatter faint luminosity functions (these differences occur fainter than the limits of the Ursa Minor dSph data). Thus we will assume that the present-day faint luminosity functions of M92 and M15 may be taken as reasonable estimates of the initial functions.

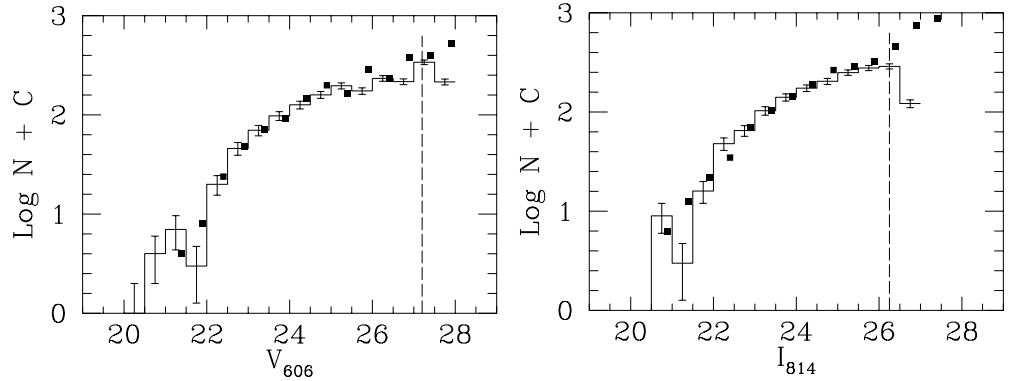


Figure 1. Comparison between the completeness-corrected Ursa Minor luminosity functions (histograms; 50% completeness indicated by the vertical dashed line) in the V-band (left panel) and the I-band (right panel) and the same for M92 (points; from Piotto *et al.* 1997).

### 3.2. Ursa Minor Faint Luminosity Function

The derived, completeness-corrected, Color-Magnitude Diagram-based, WFPC2 V-band and I-band luminosity functions for the Ursa Minor dSph are compared in Figure 1 to those for the globular cluster M92 (courtesy of G. Piotto). We find a remarkable similarity between them, down to our 50% completeness limit, which corresponds to  $\sim 0.4M_{\odot}$  (Baraffe *et al.* 1997 models).

A direct comparison between our STIS optical luminosity functions for Ursa Minor and for the globular cluster M15 is shown in Figure 2 (left panel; only those bins at least 50% complete are shown). Again, there is very good agreement in slopes of luminosity functions, and again our 50% completeness limit for the Ursa Minor data is around  $0.4M_{\odot}$ .

### 3.3. Mass Functions

The luminosity function corresponding to a mass function of slope  $-1.35$  (where the Salpeter slope is  $-2.35$ ) may be calculated using the Baraffe *et al.* (1997) models. This provides a reasonable fit to the data for M92 and for M15 (Piotto & Zoccali 1999). Further, Zoccali *et al.* (1999) found this mass function to fit their data for the faint stellar luminosity function of the bulge of the Milky Way in Baade’s window. Figure 2 shows our WFPC2 I-814 luminosity function for Ursa Minor, together with that derived from our transformed STIS LP data and the predictions from the Baraffe *et al.* models. This mass function appears to be an excellent description of the underlying IMF in the Ursa Minor dSph too.

## 4. Conclusions

As described here, the main sequence stellar luminosity function of the Ursa Minor dSph, and implied IMF, down to  $\sim 0.4M_{\odot}$ , is indistinguishable from that of the halo globular clusters M92 and M15, systems with the same old age and low metallicity as the stars in the Ursa Minor dSph. However, the

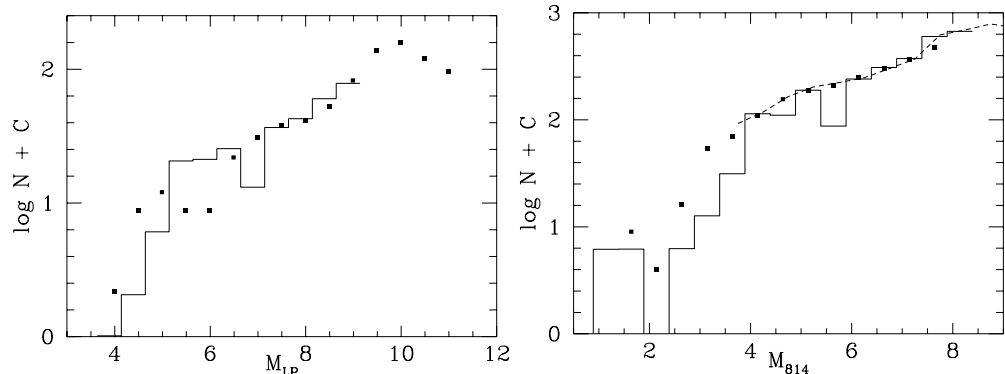


Figure 2. Left panel: comparison between the completeness-corrected STIS LP luminosity functions for the Ursa Minor dSph (solid line) and the globular cluster M15 (points). Right panel: comparison between the STIS-based I-band luminosity function of the Ursa Minor dSph (solid line), the observed I-band luminosity function (points), and the luminosity function corresponding to a power-law mass function with slope  $-1.35$  (dashed line).

globular clusters show no evidence for dark matter, while the Ursa Minor dSph is apparently very dark-matter-dominated. Thus the low mass stellar IMF for stars that formed at high redshift is invariant in going from a low-surface-brightness, dark-matter-dominated external galaxy, to a globular cluster within the Milky Way. This luminosity function, and underlying IMF, is in good agreement with those derived for the field stars of the Milky Way bulge and is consistent with the field halo and disk (e.g. von Hippel *et al.* 1996), supporting the concept of a universal IMF.

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